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Exaptation and emerging degeneracy in innovation processes

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Exaptation and emerging degeneracy in innovation processes

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In socio-economic innovation processes, exaptations emerge from processes through which an initial attribution of new functionalities to existing artifacts or organizations leads to new artifacts and eventually to new markets. In this paper, I argue that exaptation may generate degeneracy, defined as the property according to which structurally different elements provide overlapping functionalities. I propose a theoretical framework to analyze exaptation–degeneracy processes and use two case studies to show that exaptation can generate new artifacts providing functionalities similar to those provided by existing structurally different ones. This paper is intended to provide a contribution to an exaptation–degeneracy perspective in innovation theory.

Keywords: exaptation; degeneracy; innovation; adaptation

JEL Classification: O30; O33; D20

1. Introduction

In the economics of innovation literature, it is widely recognized that new products and new technologies are generated in processes in which existing products and technologies find new, often unexpected, fields of application. In Sections 2 and 3, I consider two different types of theoretical models attempting to tackle the analysis of these processes. The first uses the notion of technological convergence. The second refers to the 'adaptation through selection' paradigm using the notion of technological speciation. I critically review these kinds of explanations, arguing that they deal inadequately with the process by which new functionalities are attributed to existing artifacts, and new artifacts and new relationships between agents and artifacts are developed from existing ones.

The remainder of the paper proposes an alternative view, built on the notions of exaptation and degeneracy. In socio-economic innovation processes, exaptations emerge when an initial attribution of new functionalities to existing artifacts, capabilities and organizations leads to new artifacts and eventually to new markets. This paper is intended to provide a contribution in a subject not present in the current literature on innovation theory by focusing on the complex links between exaptation and degeneracy, defined as the property according

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to which structurally different elements are able to provide overlapping functionalities. In Section 4, I define exaptation and degeneracy and develop a theoretical framework for analyzing them. The suggested theoretical framework is based on a set of interacting processes defined at different levels of analysis and organization. In Section 5, I use two original case studies to argue that exaptations may contribute to emerging degeneracy, which, in turn, may trigger further exaptations. This process leads to the emergence of structurally different artifacts providing overlapping functionalities. In Section 6, I focus on the differences between the exaptation–degeneracy framework and the adaptation paradigm in explaining innovation processes. Concluding remarks and implications are presented in Section 7.

2. Innovation and technological convergence

The birth and development of new activities from existing ones are fundamental processes in economic and urban development (Hirschman 1958; Jacobs 1970). Similar processes were considered by Rosenberg in technological development. In a seminal essay (Rosenberg 1963), he explained the dynamics of specialization, and thus the emergence of new products, in terms of a process which he defined as *technological convergence*. Rosenberg's explanation is as follows. In all industrial sectors using machinery and metals, common processes are observable. In metal processing, a relatively small number of operations (and therefore types of machines) are required, dealing with similar technical problems, for which the solutions require an important learning process that takes place in machine production. Thus, industries that are different from the standpoint of the final product become closely linked (technologically convergent) from the technological point of view. Rosenberg argued that the process of division of labor and specialization examined by Smith ([1776] 1976), Young (1928) and Stigler (1951) must be understood in a dynamic sense. Not only does learning generate specialization, which in turn generates further learning, but learning achieved in solving specific problems also becomes available for new fields of application. In short, as has been highlighted already by Usher ([1954] 1966), in an economy based on the use of machines, the machine tool industry is a center for acquiring and disseminating new skills and new techniques. Rosenberg's theory of technological convergences is, therefore, based on a process of creation of knowledge and skills and their subsequent use in various activities that, while related, are different from the original ones.[1]

In Rosenberg's analysis, when a new product, for example, a bicycle, or a new process, for example, the use of speed steel, is introduced, this requires 'an adaptation and adjustment in capital goods industries to new technical requirements and specifications which did not initially exist' (1963, 13). Each new product or new process creates a technological imbalance that functions as a 'focusing device'. The solution of specific problems posed by this imbalance involves a process of incremental innovation supported by the continuous interactions between producers and users.[2]

Although important, this type of analysis underestimates the fact that changes in functionalities can be quite independent from the process of overcoming technological imbalances. Subsequent studies in line with Rosenberg's view have examined technological changes in terms of dominant design (Abernathy and Utterback 1975) and technological paradigms (Dosi 1982, 1984, see also Dosi and Grazzi 2010; Dosi and Nelson 2010). The roots of the innovation process are sought in a particular body of knowledge that shapes the rate and direction of technological changes and which is fundamentally driven by continued attempts to overcome the imbalances created by the process of innovation itself. Innovation is, therefore, cumulative and localized in nature (Antonelli 1995, 2011), a process in which

learning is closely related to the improvements of the techniques used. None of these studies, however, have focused on the processes of changes in functionalities and their implications.

3. Innovation, speciation and pre-adaptation

The second theoretical framework particularly relevant to the subject of this paper is the theory of punctuated equilibria, utilized to explain how new technologies can emerge using existing technologies in new application domains (Levinthal 1998; Adner and Levinthal 2002; Cattani 2006). The theory of punctuated equilibria, originally developed by evolutionary palaeontologists Eldridge and Gould (1972; Eldridge 1989), combines long periods of stasis in which species remain relatively unchanged and the phenomena of speciation, the emergence of new species descending from ancestral species. A speciation event in the evolutionary process is, in other words, the separation of a population from its antecedents, giving rise to a new population that follows an evolutionary path different from the original one. Levinthal argued that in the technological development, the application of existing technologies to new fields of application is analogous to a speciation event in biological evolutionary processes. Levinthal (1998) and Adner and Levinthal (2002) rationalized the process of successive applications of an existing technology in new fields in terms of a selection mechanism based on two fundamental features. The first is an adaptation process seen as a selection mechanism in which the new niche of application assesses the functionalities relevant to the new application – though not necessarily important in the use of the original technology. In other words, adaptation to each application requires specific selection criteria.[3] The second element of the selection process in the new field of application is given by the available resources (scientific, managerial, organizational and presence or absence of complementary skills) to support innovative activities in the new field of application.

A critical point in the explanation of the emergence of new technologies in terms of speciation is that it requires the new fields of application (new niches) with already specified selection criteria to exist before an existing technology finds a new application. Indeed, these are the criteria which guide the adaptation and development of new technologies. This setting greatly underestimates the role of the processes of changes in functionality and their consequences. Moreover, the term niche (a new field of application) is not clarified. If it is a set of relationships that are created around the emergence of a new technology, even a new field of application is an emergent property of the emergence of a new technology.

According to Cattani (2006), research on technological speciation explains how a new technology

> is generated by selection acting upon existing variation (a firm knowledge base) but does not explain how that variation was created in the first place … Nor does it explicitly address how the convergence between a firm's technological knowledge base and a new user environment comes about. (289)

To address these issues, Cattani used the concept of pre-adaptation applied to the development of a new technology. A technological pre-adaptation is defined as 'that part of a firm's technological knowledge base that is accumulated without anticipation (foresight) of its subsequent uses, though might later on prove valuable for alternative, yet unknown, applications' (289).

That the technological knowledge accumulated by a firm can be useful *ex post* in developing new products to changing external conditions – for example, on the demand side or on the competitive conditions in the product market – is well known in the literature on

innovation.[4] The explanation provided by Cattani focuses heavily on the concept of pre-adaptation. Unfortunately, the term pre-adaptation confuses rather than clarifies the process by which new products emerge (Dew 2007). In fact, 'pre'-adaptation suggests that the term refers to a process that occurs before the new external conditions with which to fit emerge. In this process, technological knowledge accumulated by a firm should be aimed at conditions that do not exist already. As argued by Dew (2007), this seems to necessitate some form of foresight that contradicts both the definition of pre-adaptation provided by Cattani and one of the basic principles of evolutionary theory that excludes all forms of foresight in the evolutionary process.

4. Toward an exaptation–degeneracy perspective in innovation theory

The main objective of this paper is to contribute to a theoretical perspective that allows us to examine the emergence of new artifacts, in a process in which the attribution of new functionalities leads to the development of new artifacts and new relationships between agents and artifacts. This section is devoted to clarify two key notions of this perspective – the notions of exaptation and degeneracy in innovation processes – and to develop a theoretical framework to analyze the emergence of innovations.

4.1. Exaptation and innovation

The term exaptation was coined by evolutionary biologists Gould and Vrba (1982; Gould 2002) and refers to those features that are useful for survival but not selected for this purpose. In a well-known example, feathers, which originally had the function of thermoregulation, were later co-opted by birds for flying through a process that has made them 'apt' for such new use. Consequently, it cannot be stated that feathers are ad-apt for a use (flying) for which they were not selected. They are *apt* for flying in virtue of their *ex* form: they are *ex-apt*. In other words, feathers were exapted for a purpose different from the original one. An exaptation is the result of a *process* of change, a process in which all the structural conditions necessary for the new functionality are developed. Note that in biological systems, such a process is not driven by any form of foresight and often has a contingent nature. Contrary to Cattani's claim (2006, 290), this is precisely why the feathers of birds cannot be considered a pre-adaptation to their use for the flight.

In human activity, exaptation can be defined, in very general terms, as a result of a process through which an initial attribution of a new functionality to existing outcomes – whether they are artifacts, organizations, scientific achievements or cultural models – leads to new outcomes. New functionalities can emerge in a deliberate process of research or in a non-intentional way. In any case, in order to build a theoretical framework, it is essential to examine the process by which the initial attribution of a new functionality leads to new outcomes. In what follows, the process of exaptation is examined with respect to the emergence of new artifacts.

Artifacts include a wide range of objects or interactions, both tangible (consumer goods and capital goods) and intangible (know-how, services or legislations). I define an artifact in terms of three interacting elements: its structure, its functionalities and its processes of transformation.[5] The *structure* of an artifact is determined by its material characteristics, by the processes of transformation that the matter has undergone as a result of human labor oriented by a project and by the way in which its different components, which are themselves artifacts, interact. The *functionalities* of an artifact depend on the properties attributed to it in relation to its usefulness for some purpose. The interaction between structure and

functionalities is governed by the *processes* through which the functionalities are attributed and the matter is transformed. Hence, artifacts emerge from a social process. Individuals must come into contact with other individuals in order to generate the flow of information, functionalities, technical knowledge and capabilities by which an artifact *becomes* generally utilized and produced. Note that this definition of artifact allows us to define with precision a technology as a complex artifact and that it implies that the knowledge base (information, technical knowledge and capabilities) is distributed among different agents.

Artifacts are currently produced, sold and used within a system of interactions between producers, sellers and users. In a market system, these interactions are organized through the emergence of appropriate forms of coordination. In traditional neoclassical economic theory, markets are anonymous and abstract entities in which supply and demand functions determine clearing prices. Hence, market relationships are reduced to market transactions between maximizing agents coordinated by the price mechanism. In the strongly reductionist formulation of neoclassical economic theory, markets do not have a specific history. The origin and development of specific relationships that give rise to markets do not matter. Instead, we need a market definition that allows the examination and reconstruction of the market relations in different historical and social conditions. From this perspective, a market system can be defined as a heterogeneous collection of agents – producers, sellers and users – whose interaction occurs around a heterogeneous set of artifacts giving rise to recurrent patterns of interactions (Lane and Maxfield 2005). In this formulation, markets are entities in which particular processes of interaction between agents and artifacts take place and in which a series of activities are generated. These range from design, production and exchange of artifacts to the creation of new attributions of functionality, of new capabilities and of new artifacts and new patterns of interaction. Market systems are supported by particular 'scaffolding structures', such as trade and professional associations and other key role agents, such as services providers and installers (Lane and Maxfield 2005). Hence, the patterns of interactions in a market system give rise to evolving families of artifacts in which new knowledge and new information are generated.

What are the theoretical foundations of exaptation in innovation processes? Dew, Sarasvathy, and Venkataraman (2004, 75) sought the answer in two characteristics of artifacts, and of technologies in particular. The first characteristic is that a technology as a complex system is characterized by the property of 'near decomposability' (Simon [1962] 1999) allowing exaptations to take place. The second feature of technologies is that they can give rise to a virtually endless and unpredictable list of possibilities and consequences. The potential uses of an artifact – or of its components – are the necessary conditions for a process of transformation that from existing artifacts leads to new artifacts. The present contribution to a theory of exaptation focuses on two general processes: (a) the process of attribution of new functionalities and (b) the process through which new functionalities may generate new artifacts and new markets. An exaptation process includes a process of 'aptation' in which new artifacts, apt to provide the new functionalities, emerge along with the creation of new complementary products and improvements in existing products.[6]

A classical example of exaptation is the phonograph to which Edison attributed the functionality of serving as a dictating machine. In addition to this functionality, Edison, in an article published in 1878, specified nine other possible uses of phonograph:

> provide 'talking books' for the blind; teach public speaking; reproduce music; preserve important family sayings, reminiscences and the last words of the dying; create new sounds for music boxes and musical toys; produce clocks capable of announcing the time and a message;

> preserve the exact pronunciation of foreign languages; teach spelling and other rote material; and record telephone calls. (Basalla 1988, 139–40)

Of all these possibilities, the phonograph was successfully co-opted as a tool for automatically playing popular music in the first jukebox, only through a process of attribution of a new functionality to it. This, with appropriate developments of complementary technologies, leads to the first major use of the new technology.

Exaptation phenomena are common in innovation processes.[7] The analysis of the process of exaptation is a key element to a better understanding of the dynamics of the innovation processes. Lane (2011) argued that exaptation introduces a positive feedback in innovation processes, and Bonifati (2010) argued that it is a foundational concept of a complexity theory of innovation.[8] According to Dew et al. (2011), exaptations broaden the variety of transformation types in technology and market evolution. The important point is to develop a theoretical framework that allows us to analyze these processes.

4.2. Exaptation and degeneracy

When new functionalities are attributed to existing achievements of human activity (whether they are artifacts, organizational forms or cultural models), exaptations can generate new structures that can provide overlapping functionalities to those provided by existing different structural elements. If this happens, the process of exaptation generates degeneracy. The etymological meaning of the term degeneracy indicates a change in the structure of some element from its original form (Mason 2010). For a long time, the term *degeneracy* was surrounded by a strong pejorative connotation due to the acceptance of a normative assumption according to which, within living and cultural systems, a degenerate element was a departure from its original 'perfect' form.[9] Nevertheless, more recently, the concept of degeneracy has become widely used in evolutionary biology in a value-free scientific definition referring to the way in which systems are coded or mapped (Mason 2010). I use the term degeneracy in its scientific meaning according to which structurally different elements are able to provide overlapping functionalities. It follows that in the presence of degeneracy, 'different structures have similar consequences' (Edelman and Gally 2001).

The key feature to understanding degeneracy is the relationship between structure and function. Degeneracy is characterized by polymorphic (many structures) and iso-functional (same function) elements with a *many-to-one* mapping between structure and function. In more general terms, if we consider that degenerate elements can be multi-potentials – that is, they can deliver different outputs in different contexts – degeneracy is characterized by polymorphic and poly-functional elements with a *many-to-many* mapping between structure and function (Edelman and Gally 2001; Whitacre and Bender 2010). Degeneracy is – and must be kept carefully – distinct from redundancy. 'Functional redundancy' is a property whereby in a system identical elements perform the same function in any context. In other words, redundancy is characterized by isomorphic and iso-functional elements and implies a *one-to-one* mapping between structure and function.

In biological systems, degeneracy is present at all levels of organization, from genetic code to interanimal communication (Edelman and Gally 2001). For example, different base sequences can code for one amino acid, as the different combinations of adenine, uracil and cytosine can code for the amino acid isoleucine (Mason 2010). Another well-known example of degeneracy in neurobiology is the convergent–divergent connectivity of the human brain. For example, different brain structures can influence motor function, in series or in parallel.

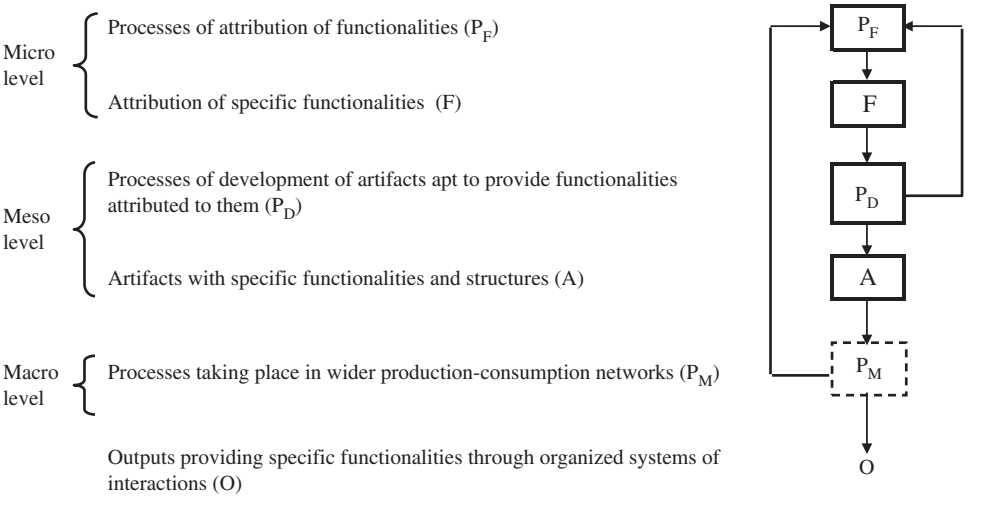

Figure 1. Circular processes of interactions between agents and artifacts.

As a consequence, after a localized brain lesion, frequently alternative pathways ensuring the same functionality emerge (Edelman and Gally 2001).

In human activity, an example of degeneracy concerns the similar but not identical linguistic structures used in human communication to convey the same meaning. Although less studied, degeneracy is widely present even in production and innovation systems in which many interlinked activities produce a wide variety of goods and services. Lane (2010), for example, argued that industrial districts owe their robustness to overlapping different structures which cooperate to maintain key functionalities at the system level.

4.3. A theoretical framework

I propose to examine relevant aspects of the processes of innovation in terms of a theoretical framework which allows us to capture how exaptation emerges. This theoretical framework is essentially based on processes that activate processes[10] and can be illustrated distinguishing three different, albeit interacting, levels of analysis and organization – microlevel, mesolevel and macrolevel[11] (Figure 1).

The attribution of functionalities occurs at the *microlevel* through interactions between agents and artifacts around a given artifact (or a given family of artifacts) – with a given structure apt to provide the given functionalities. These interactions are organized around the processes of production, storage, delivery and consumption of artifacts. At the microlevel, individuals (or groups of individuals) attribute functionalities using (or producing) existing artifacts and communicate the new information to the potential producers (or to potential users). Through these processes (P_F), specific functionalities (F) are attributed.

At the *mesolevel*, recurring patterns of interaction emerge organized around attempts made by producers to produce, interacting with users, artifacts with appropriate structures to provide functionalities attributed to them. Complementary technologies can be developed and functionalities can be better defined by users and/or by producers. So, functionalities can co-evolve with the development of technologies and products. At the mesolevel, processes of development of artifacts apt to provide functionalities attributed to them (P_D) give rise to artifacts with specific functionalities and structures (A).

The third level of analysis, the *macrolevel*, focuses on a higher level of coordination in order to sustain and consolidate the patterns of interactions specific to the microlevel and mesolevel. Coordination at the macrolevel is essential to support the processes of attribution of functionalities (microlevel) and *aptation* (mesolevel) through which artifacts assume an apt structure to provide functionalities specifically attributed to them. This higher level of coordination involves organization within the firm, the relationships between firms and the relationships between producers and customers. In other words, to be currently produced and sold, an artifact must be placed in a wider network of interactions where there may be several intersections with other patterns of interactions. For example, artifacts require sales networks to sustain and create demand and inter-firm supply agreements to implement supply. Through macro-processes (P_M), relatively stable relationships between production and consumption emerge in organized systems of relationships between agents and artifacts.

A crucial aspect of the above theoretical framework concerns two mechanisms of activation of the processes of attribution of functionalities. Functionalities can emerge both from producers in the process of developing a product (P_D at the mesolevel) and from users and producers which in the wider production–consumption networks interact with many other agents and artifacts (P_M at the macrolevel). Figure 1 presents these two mechanisms of activation of the processes of attribution of functionalities as two feedbacks between mesolevel and macrolevel processes and microlevel processes of attribution of functionalities. If the outcome of this set of processes is that functionalities attributed to artifacts do not change, the process of production and consumption reproduces itself with unchanged functionalities. In this case, the overall process produces as output production and consumption of artifacts providing specific functionalities through organized systems of interactions (O).

However, as I describe in the next two sections, this is not a necessary outcome. Attributions of new functionalities to existing artifacts can lead to new, structurally different artifacts (or to a new use of existing artifacts) currently produced and consumed as exaptations of the already existing artifacts. Whether a structurally different artifact is generated or not, an exaptation always involves a new relationship between structure and functionality giving rise to a transformation in the relationships between agents and artifacts in the production–consumption process (Bonifati 2010, 753–4).

5. Exaptation, emerging degeneracy and innovation: two case studies

Here, I use the framework put forward in the preceding section to show, through two historical examples, how in exaptation–innovation processes degeneracy may emerge and how, at same time, degeneracy may trigger further exaptation processes.

The examples relate to the new artifacts which emerged from the use of the printing technology in the second half of the fifteenth century in Florence.[12] Printing technology transformed the relationship between production and consumption, long before the industrial revolution did so for the majority of manufactured goods. Studying in detail the changes in relationships between agents and artifacts around a new family of artifacts – the different types of printed books – offers the opportunity to explore the ways in which a technology, which originated with the generic function of reproducing texts, was exapted in specific ways. Making it possible to reproduce texts in many copies, fast and cheaply, printing technology opened up new potentialities. At the same time, it required a qualitatively new relationship between production, technology and consumption (Bonifati 2008, 2010). Unlike manuscripts, in general, printed books are not produced on order but for a *potential* demand. It follows that printed book production needs to be funded in advance of the

actual sales. The search for links with potential customers became a necessary condition for production and an active force in building a market system.[13]

According to the artifact definition given in Section 4.1, the book as an artifact may be identified by

(a) its structure, depending on technical and physical properties (reproduction techniques and material used as support for the reproduction of texts) and on exterior characteristics (size, fonts, presence/absence of illustrations, etc.),
(b) its functionalities attributed by readership within the limits imposed by its structure and content (subject and language) and
(c) the processes through which structure and functionalities emerge.

For the present purposes, it is important to introduce a distinction between generic (or potential) and specific functionalities. For books as a family of artifacts, there is a *potential functionality* inherent in the written text: preserving in written form a multiplicity of human activities, ranging from speculative thought to description of economic activities, transmission of emotions and representation of images. The *specific functionalities* that readership attributes to each type of book depend on the content and exterior characteristics of the books and, more importantly, on the processes through which the purposes for each type of book emerge. In the mid-fourteenth century in Italy and Europe, different types of manuscripts were produced, such as liturgical books in large format, prayer books of smaller size, academic texts, especially of legal arguments, and humanistic books, in particular, the texts of Latin and Greek classical authors. University manuscripts were produced, on a large scale, in Paris and Bologna, sites of the most important and oldest universities in Europe. Florence was the most important production center of humanistic manuscripts sold throughout Europe. Manuscripts were reproduced on order, through a complex system of relations – governed by appropriate contracts – between booksellers, stationers, scribes and clients.

In Florence, the first books were printed in 1471, in a press located in the Dominican convent of San Jacopo di Ripoli. They were mainly religious and devotional texts, texts of vernacular poetry and grammars: books very different from the precious humanistic manuscripts that Vespasiano da Bisticci, the most prominent bookseller in the first half of fifteenth-century Florence, sold to the *élites* (intellectual as well as social and political) in Italy and Europe. The first books printed in Florence were produced for and used by a popular readership assigning specific functionalities to different types of books, such as acquiring primary education through school books or engaging in religious devotion through reading devotional tracts. Production and consumption of popular books occurred in organized market systems of written communication built around the relationships between printers, publishers, peddlers and potential clients. In fifteenth-century Florence, the printing technology was co-opted by other organized systems of communication. I illustrate this process of exaptation with two case studies.

The first refers to the system through which Savonarola intervened in the political–religious conflict in the last decade of the fifteenth century in Florence. Savonarola used the verbal sermon, an artifact with the generic function of expressing a message of religious or moral content, assigning it a specific functionality: to communicate his message of strong criticism of the morality of the church. Through his verbal sermons, he entered into communication with the public who listened to him and, through the discussions that followed, indirectly with a wider audience. In a city like Florence, with a strong tradition of popular

participation in public life, a system of relationships was organized around Savonarola's verbal sermons through which the verbal sermons achieved the specific functionality assigned to them. In this organized system of communication, Savonarola intentionally used print in new ways. The sermons began to be transcribed by the Florentine notary Lorenzo Violi. The texts were reviewed by Savonarola himself, who intervened actively in editing his sermons' editions, also by adding illustrations in the text in order to reach a wide audience. Most editions of the sermons were published by the printer-publisher Bartolomeo de' Libri, and some by the printer Francesco Bonaccorsi for the publisher Piero Pacini da Pescia, who, more than any other Florentine publisher at that time, included illustrations in the volumes he produced. In other words, Savonarola attributed to printed texts the specific functionality that he assigned to his verbal sermons, to communicate a particular message of strong criticism. The printed texts of the sermons perform this task through the system of relationships that the author, printers, publishers and booksellers had with a readership that, in a city like Florence with a high level of literacy,[14] was potentially larger than that able to attend the sermons.

The printed texts of Savonarola's sermons, in the form of short books or pamphlets, represent an exaptation of the already existing printing technology. They derive from a new functionality attributed to print that generated a new system of relations between agents and artifacts. This exaptation process gave rise to a new type of book intended to intervene in the public life of the city, with a new link between the author and the potential readership. It is important to emphasize that, as a result of this process, for a certain period, two structurally different artifacts – the verbal sermons delivered in the church and sermons as printed texts – fulfill, in two different organized systems of communication, at least in part the same functionality of communicating a particular message. This result represents a case of emerging degeneracy. When the verbal sermons of Savonarola were forbidden by the Pope, and during the period that Savonarola respected this prohibition, the circulation of the printed texts of sermons was the only one of these communication systems in action. Savonarola's printed texts, mostly sermons, played a significant role in the market system of printed books in Florence: they constituted about 14% of all editions of fifteenth-century Florence. This percentage rose to 30.3% in the period between the papal excommunication in 1495 and the execution of Savonarola's death sentence in 1498 (Bonifati 2008, 222).

At the beginning of printing, and for a long period, compared with verbal communication, printed texts provided additional functionalities: they could be reproduced, stored, delivered and used in places and times different from those where they were originally produced. These functionalities provided printed texts with an impact which was very different from that of verbal communication. For example, the impact of Savonarola's sermons in their written version was no longer restricted to Florence or to Savonarola's lifetime. In a qualitatively different way and on a much larger scale, this is also true for Luther's published sermons, which were the greatest publishing triumph of the first century of print and had the most far-reaching effects imaginable (Edwards 1994).

Figure 2 provides a representation of the exaptation–degeneracy process in terms of the theoretical framework put forward in the previous section. Savonarola's verbal sermons with the specific functionality of providing strong criticism of the morality of the church emerge from the interaction between (a) a microlevel process of attribution of functionality by Savonarola and by the public which he addressed; (b) a mesolevel process in which the sermons were realized with a particular modality and in particular places; and (c) a macrolevel process in which a wider interaction around Savolarola's sermons emerged.

This macrolevel of interactions fuels the microlevel focalization process of attribution of functionality. When, in the wider system of interactions around Savonarola's sermons

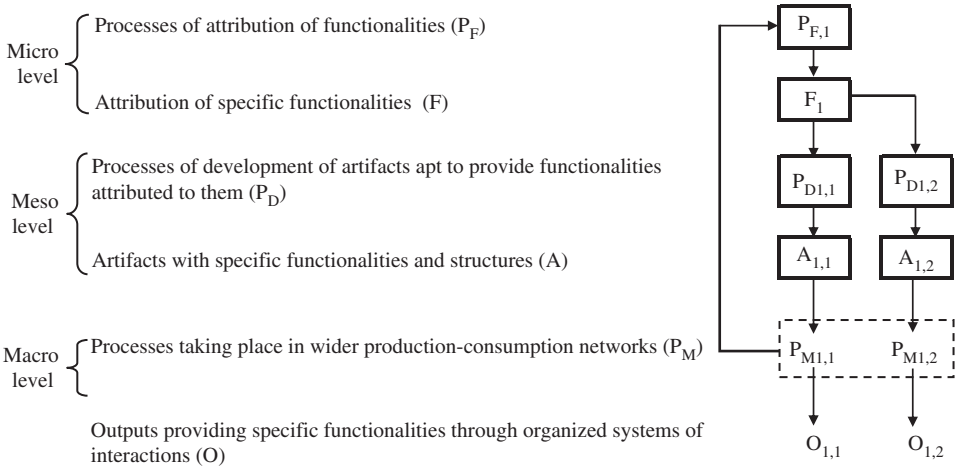

Figure 2. An example of degeneracy emerging from exaptation. The first subscript number indicates the functionalities and the second the structurally different artifacts. Macro-processes in a wider context are delimitated by a dashed rectangle. Legend with reference to the first case study: $A_{1,1}$, verbal sermons with the specific functionality to provide a strong criticism to the morality of the church; $O_{1,1}$, verbal sermons providing a specific functionality supplied through organized systems of interactions; $A_{1,2}$, printed sermon with the specific functionality to provide a strong criticism to the morality of the church; $O_{1,2}$, printed sermons providing a specific functionality supplied through organized systems of interactions.

(macrolevel), the sermons began to be transcribed a new microlevel focalization process was activated. Through this, the functionality of providing strong criticism of the morality of the church was attributed to the printing technology, already existing to provide specific functionalities different from this. At the mesolevel, this gives rise to a new artifact, that is, a new type of printed texts. At the macrolevel, a new wider system of interactions around Savonarola's printed sermons emerged, fueling the microlevel focalization process of attribution of functionality to the new artifacts (Savonarola's printed sermons). This overall process gives rise to degeneracy. Two structurally different artifacts – verbal sermons and printed sermon – provide overlapping functionalities. In other words, in the exaptation process new artifacts, which until that time had not existed, emerged providing at least in part the same functionalities of already existing artifacts.

The second case study of exaptation and emerging degeneracy refers to the modalities in which print was co-opted by the communication system connected with the art of singing legendary stories in the streets and courtyards of Italian cities, well established since the thirteenth century.[15] Until the late fifteenth century, Florence was the home of ballad singers, the city with the oldest and most consolidated tradition of this form of communication. Ballad singers performed in the square opposite the church of San Martino in the same street where the San Jacopo di Ripoli press was located. They sang legendary stories of the *chansons de gestes*, lives of saints and satirical sermons to an audience of listeners of all social classes.

The printing technology was co-opted by this verbal communication system through the interaction between ballad singers and the printed texts. In Florence, printed texts were distributed not only through booksellers – who could also be editors and printers – but also through peddlers. Thus, the books were sold in the streets. The San Jacopo di Ripoli press, for example, used ballad singers and *ciurmatori*[16] to sell books. In this way, ballad singers

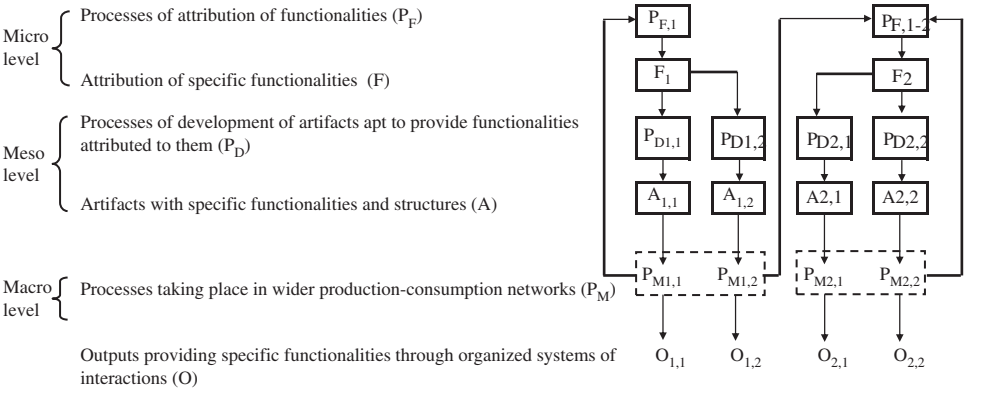

Figure 3. An example of degeneracy emerging from exaptation and of exaptation triggered by degeneracy. The first subscript number indicates the functionalities and the second the structurally different artifacts. Macro-processes in a wider context are delimitated by a dashed rectangle. Legend with reference to the second case study: $A_{1,1}$, ballad singers with the specific functionality to provide access to the popular literature (F_1); $O_{1,1}$, ballad singers providing a specific functionality (F_1) supplied through organized systems of interactions; $A_{1,2}$, printed ballad with the specific functionality to provide access to the popular literature (F_1); $O_{1,2}$, printed ballads providing a specific functionality (F_1) supplied through interacting systems of interactions; $A_{2,1}$, ballad singers with the specific functionality to provide interpretations and disclosures of contemporary events (F_2); $O_{2,1}$, ballad singers providing a specific functionality (F_2) supplied through organized systems of interactions; $A_{2,2}$, printed ballad with the specific functionality to provide interpretations and disclosures of contemporary events (F_2); $O_{2,2}$, printed ballads providing a specific functionality (F_2) supplied through organized systems of interactions.

and *ciurmatori* came into contact with new artifacts – the printed text. This interaction produced an unexpected outcome. Ballad singers and *ciurmatori* began to order the printed texts of ballads and short stories of the traditional popular literature to the San Jacopo di Ripoli press:[17] they attributed a new functionality to the printing technology and developed new products. These short printed texts, sometimes only a single sheet, are an exaptation of the already existing printing technology. As a result, the functionalities attributed by the users to popular literature could now be achieved through two structurally different artifacts – ballad singers' performances and printed texts – provided by two different, but in this case adjacent, organized systems of communication.

In others words (Figure 3), the functionality attributed to ballad singers' performances, which allow access to popular literature (microlevel), gives rise to a particular artifact, the ballad singers' performances realized in particular time and place (mesolevel). Exaptation and degeneracy occurred when the ballad singers – interacting in a wider context (macrolevel) with new artifacts, printed books they began to sell – focused the process of attribution of functionality on printed texts. Through this process, the same functionality was attributed to a different artifact (microlevel). A new artifact – printed texts of ballads – was realized (mesolevel) and a new wider interaction system between ballad singers and the public attending their performances emerged (macrolevel).

Both sung and printed ballads delivered the possibility of enjoying popular literature. However, the sung ballads delivered functionalities not obtainable from the printed ones, in terms of the emotional and esthetic pleasures linked to the collective experience of music. The printed ballads offered, instead, the functionality to read the legendary stories at times and in places different from those they were presented in the squares. Sung and printed

ballads co-existed by virtue of their specific but overlapping functionalities that, for a time, supported each other.

These examples show how the specific functionalities attributed to the printing technology generated differently organized systems of interactions and different artifacts through which these specific functionalities became usable by producers and users. These new artifacts (the printed sermons and ballads) provided in part the same functionalities of the verbal sermons and ballad singers and in part new functionalities which emerged with the emergence of the new artifacts. In the cases discussed above, we can verify that different types of printed books, the result of exaptation processes, can co-exist with structurally different artifacts – such as alternative verbal forms of communication – providing overlapping functionalities. In this sense, exaptations generate degeneracy.

Degeneracy enables further exaptation. In an organized system of relationships between producer, traders and users, new functionalities and new artifacts can emerge. For example, as has been highlighted above, when ballad singers and *ciurmatori* started selling books for the San Jacopo di Ripoli press, they related to a particular readership and with a specific book producer. From this relationship emerged their new activity as 'publishers' of popular cheap books (which was linked to the pre-existing activity of verbal performances). Later, from this new activity, an innovation emerged: ballad singers and *ciurmatori* began to use the songs and printed texts to offer the public not just traditional popular literature but also interpretations and disclosures of contemporary events. In other words, they attributed a new functionality to verbal and printing technologies and began to develop new products – songs, stories and related printed texts inspired by contemporary events – that they offered as singular or combined products (Novati [1907] 2004, 99). These new products represent an exaptation triggered by degeneracy. In terms of Figure 3, the possibility offered by two different artifacts – songs and printed texts of popular literature – to provide overlapping functionalities triggered a new functionality: that of allowing access through songs and printed texts to interpretations and disclosures of contemporary events (microlevel). In this way, new artifacts were developed as an exaptation of the existing artifacts: songs and printed texts inspired by contemporary events (mesolevel). A new system of organized interactions emerged around these new types of artifacts (macrolevel).

The processes of exaptation–degeneracy occur in conditions of ontological uncertainty (Lane and Maxfield 2005). None of the new print artifacts, the new agents and the transformations in relationships between agents related to these processes were predictable. The key consideration here is that in the process of exaptation–degeneracy, new artifacts providing at least in part the same functionalities as existing artifacts emerge from existing market systems, that is, from existing organized systems of relationships. As seen in the two examples considered, the printed texts of Savonarola's sermons and of the traditional ballads emerged from the relationships around the already existing artifacts, Savonarola's critical verbal sermons and the sung ballads, respectively. In other words, in the two case studies, the existence of market systems has made it possible for agents to act in constructing new products and new markets undertaking a sequence of interactions through which they oriented their activities toward transforming particular zones of agent–artifact interaction space.[18]

6. Exaptation (and degeneracy) versus adaptation

In Section 3, I argued that in the explanation of innovation processes in terms of the notion of speciation, the dominant idea is that technology follows a kind of trajectory guided by a process of adaptation to new application domains. According to this view, the technology

'colonizes' new fields of application in a kind of top-down process. I argued that this setting requires the existence of pre-conditions – niches with their own selection criteria and pre-adapted capabilities – assumed *a priori*, rather than as the result of a process that, from existing artifacts, leads to new artifacts. It follows that the process by which new functionalities are attributed to existing technologies and new artifacts are developed from existing ones is inadequately dealt with. Bonifati and Villani (forthcoming) argued that the analysis of exaptation represents a possible alternative to the 'adaptation through selection' paradigm in examining innovation dynamic processes. The 'adaptation through selection' paradigm focuses on adaptation to a given functionality overlooking that new functionalities can be attributed to artifacts or organizations 'selected' for other purposes, giving rise to new artifacts or new organizations. Through a selection–variation process, the origin of an artifact or of an organization should be derived from its current functionality. In exaptation processes, instead, artifacts and organizations are created by using in a new way artifacts, including technologies, and organizations already available for other purposes. It follows that in the exaptation-based perspective, the origin of the artifacts and organizations cannot be derived from their current functionality.[19]

To grasp the differences between the exaptation and degeneracy framework and the adaptation paradigm, it is useful to use the two examples utilized by Levinthal and Cattani. The example considered by Levinthal is the development of wireless communication technology (Levinthal 1998; Adner and Levinthal 2002). This technology started as a laboratory tool, an artifact consisting of a radiator (transmitter) of the waves and a detector (receiver), devised by Hertz to test Maxwell's theories on electromagnetic waves (Basalla 1988, 97–101). In its initial use, the functionality attributed to this artifact was to accurately measure the electromagnetic waves. By applying Hertz's laboratory tool to a new and different scope, Marconi developed a new artifact – the wireless telegraph – with a new functionality, that of distance communication for commercial purposes.

Let us briefly consider this case in terms of the exaptation–degeneracy framework. Until 1896, the functionality to communicate at distance was provided for the system of wired telegraph. At the microlevel, the same functionality was assigned by Marconi to a different system of remote communication based on the use of electromagnetic waves. For this innovation, Marconi used the knowledge developed in the technology of the telegraph and the knowledge developed in the use of electromagnetic waves. Thus, to Hertz's wireless laboratory communication system a new functionality was attributed. This triggered a mesolevel process, changing the structural characteristics of the artifact (i.e. Hertz's wireless laboratory communication system) to make it apt to provide the new functionality (i.e. the wireless remote communication). A new artifact emerged as an exaptation of the original Hertz's laboratory tool. At the macrolevel, a new organized system of relationships between agents and artifacts emerged. In 1897, Marconi founded the Wireless Telegraph and Signal Company to produce the new artifact, but was not clear what markets it would serve. Marconi had to build the market. From the initial first customers – the British army and navy – a new and broader market was built. To promote the use of the new artifact by the large maritime industry, a new subsidiary was established and radio operators were trained to implement the use of the radiotelegraphy for ship-to-store communication. This is the case in which an exaptation has given rise to a new artifact (wireless technology) with functionalities overlapping those of an existing structurally different artifact (wired technology).

In a new organized system of relationships between agents and artifacts, new functionalities can be activated. To continue with the example of wireless communication, the

new organized system of relationships around the wireless telegraphy activated a new functionality of distance communication: the transmission of sound. This new functionality was activated in connection with the emergence of new knowledge and new capabilities in wireless telegraphy. New technologies that allowed new transmitters and receivers to be built were developed. This research eventually led to the development of the cathode ray tube (vacuum tube). Using the vacuum tube, a system that allowed continuous transmission of the waves to transmit voice was developed. This new technology formed the basis for new artifacts – wireless telephony (radiotelephony) and broadcast radio, a new artifact allowing voice communication between one and many.

In the theoretical framework based on the process of speciation, a new field of application (a new niche) is supposed to exist with its own selection criteria. However, wireless telegraphy did not exist before a new functionality was attributed to the instrument used by Hertz in the laboratory. All the characteristics of this new field of application of wireless communication technology, and therefore the new application domain, emerged as a result of processes activated by the new functionality of distance communication attributed to a technology which had hitherto been used only in a physics laboratory. Note that in this process, new knowledges, new functionalities and new artifacts co-evolve without requiring the existence of pre-established market niches to be colonized by a new technology. Furthermore, if we consider the macrolevel as a kind of environment in which interactions around production and consumption are organized in a wider context, our theoretical framework allows us to show immediately that it interacts with processes at the microlevel and mesolevel.

Analogous considerations can be applied to the case of the development of optical glass fibers examined by Cattani (2006). From 1851–1966, Corning Inc. developed considerable experience and knowledge in the production of special glass resistant to high temperatures (Pyrex and the glass used for laboratory experiments), which was then used in the production of fiber optics. In mid-1966, a new functionality for optical glass fibers emerged. The British Post Office (BPO), which at that time was operating the British telephone network, was in search of a system of data transmission that better than the copper-based fiber system used until then with a limited capacity of transmission. The research results then available indicated that theoretically optical glass fiber could be used as a much more powerful means of transmission. To this end, in June 1966, the BPO invited several glass-manufacturing companies, including Corning Inc., to a meeting to inform them of the decision to renew the infrastructure network in the country by substituting the copper-based fibers with optical glass fibers. This event, along with developments in science regarding the possibility of using glass fibers for transmission of data, was the start of a new field of application of glass technology: optical fiber technology. Corning's success in developing the new fiber optic technology is interpreted by Cattani in terms of a pre-adapted technological knowledge base accumulated previously in the production of special glasses and later adapted through well-defined selection criteria to a new application domain. However, the technological knowledge base was not accumulated with reference to something that did not already exist, but for the functionality at that time attributed to a special type of glass. Thus, this base of technological knowledge accumulated by the firm can under no circumstances be considered a pre-adaptation, as Cattani argued, unless we assume some form of foresight. The attribution of a new functionality to the glass fibers did not mean the existence of a new field of application for knowledge accumulated for a different use. The new field of application required research efforts and the ability to use existing capabilities in a different way.

The processes from which an exaptation emerges differ from the phenomena that Arthur (2009) called 'adaptive stretch'. According to Arthur, these phenomena are related to the lock-in processes that give rise to the success of an 'old' over a 'new' technology. As a consequence, Arthur argued that 'when a new circumstance comes along or a demand for a different sphere of application arrives, it is easier to reach for the old technology … and adapt it by "stretching" it to the new circumstances' (2009, 140). Instead, the processes of exaptation, as analyzed through the theoretical framework suggested in this paper, focus on the processes of change triggered by a process through which new functionalities are attributed to existing artifacts.

An external event can induce changes in the use of a technology or an organization – as testified by the many cases of peaceful uses of technologies originally developed for military purposes (the so-called dual-use technologies). The exaptation-based perspective suggests that to capture the wider effects of an initial change, we need to reconstruct the changes in relationships between agents and artifacts in the interaction between the attribution of new functionalities (microlevel), the development of new artifacts apt to provide new functionalities (mesolevel) and the emergence of new organized systems of relationships between agents and artifacts (macrolevel). In this perspective, the model used by Marquis and Huang (2010) in their recent work on the legacy of founding institutions in US commercial banks does not seem to be adequate to explain in terms of exaptation that 'imprinted capabilities originally developed for bank branch management become useful for a new purpose – bank acquisition management and integration – after an environmental shift' (1442). Marquis and Huang define exaptation as the use of management capabilities developed to manage the dispersed units in a given context (dispersed branching management before a bank's deregulation) for another use in a different context (policy of acquisitions after deregulation). However, Marquis and Huang's theoretical framework seems to be inappropriate for analyzing exaptation processes. It is a unidirectional framework, running from 'durable imprinted capabilities to manage and coordinate geographically dispersed locations' to 'the greater propensity to acquire other banks' as a result of adaptive, and non-exaptive, activities after a change in banking legislation (see the model depicted on page 1448). Under their theoretical framework, after the change in the external environment, the banks which already possessed the appropriate capabilities to acquisition policy found (obviously) an advantage in this policy in the new external environment. Marquis and Huang did not examine any process of change of functionality attributed to the existing capabilities. The theoretical framework of Marquis and Huang seems to be closer to a theory of adaptation through selection – in which organizational routines are selected by the market (Nelson and Winter 1982; Winter 1990) – than to a theory of exaptation, according to which changes in the environment, in the attribution of functionality and in the processes of transformation of organizational capabilities interact.

7. Concluding remarks and implications

The exaptation–degeneracy perspective proposed in this paper captures three aspects of innovation processes that seem to have been overlooked by the theories of innovation based on the 'adaptation through selection' perspective: the microlevel processes of attribution of new functionalities; the mesolevel processes through which new artifacts are developed from existing ones but with new functionalities; and the macrolevel processes through which new markets are created to sustain current production and consumption. The lack of attention to these processes in adaptationist theories of innovation comes from the structure of these theories in which specific selection criteria play a predominant role in the adaptation process.

In this framework, the functionalities are considered as selection criteria and therefore considered as designed in a well-defined way in order to guide the adaptation process in the new field of application. The development of new products is examined in terms of the availability of resources – technical and managerial knowledge – already present in the new field of application. The conditions at the macrolevel for the construction of markets on both the demand and supply sides are under-researched.

The two case studies examined with the aid of the theoretical framework proposed in this paper show that new functionalities are attributed to existing artifacts and technologies in existing organized systems of relationships giving rise to the transformation of existing artifacts in new artifacts, new identities of existing agents and new agents. New functionalities, new artifacts and new markets emerge through this set of processes. None of these processes of transformation in the agent–artifact interactions space were predictable. In others words, exaptation–degeneracy processes occur in conditions that Lane and Maxfield (2005) defined as ontological uncertainty. These conditions, while are not considered in the perspective based on adaptation through selection, are essential to examine how in existing market systems agents undertake a sequence of interactions through which they transform existing agent–artifact interactions giving rise to new artifacts and new markets.

Exploring the complex links between exaptation and degeneracy opens a wide range of possibilities in the analysis of innovation and development processes. In very general terms, the processes of exaptation–degeneracy are a manifestation of systems that create a high degree of flexibility and robustness in the face of environmental changes.[20] Further research is needed to study the different forms of degeneracy both at the market level and at the firm level.

At the market system level, exaptation–degeneracy processes, as discussed in this paper, extend the possibilities of creating new artifacts by combining old and new functionalities attributed to existing artifacts and capabilities. Empirical research should uncover, for example, the links between new information and communication technologies and communication systems and technologies that already exist in providing new functionalities, new artifacts and new market systems. This is the case of the appearance of new electronic devices for presenting and reading books and newspapers, which in any case, at least for now, continue to be printed as well. An open question concerns the permanence of degeneracy in the form of structurally different artifacts able to provide overlapping functionalities. In this regard, a better and deeper understanding of the relationship between functionalities and structural characteristics of the artifacts is needed to better grasp the dynamic process of creation (and destruction) of overlapping functionalities.

At the firm level, the processes of exaptation–degeneracy shed new light on the processes through which firms develop and use new capabilities. As argued by Penrose (1959), the core of these processes lies in the new functionalities attributed to existing and new resources. In particular, in a system of interactions in which the process of exaptation–degeneracy is realized, firms can gain access to different structurally organized capabilities providing overlapping functionalities. Accordingly, resources and capabilities are linked through a many-to-many system of relationships. This is a conclusion that seems to question a version of the 'resource-based view of the firm' too rigidly focused on a one-to-one relationship between resources and capabilities within the individual firm.

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Notes

1. Strassmann (1963), in a comment to Rosenberg's essay, noted that

> what makes machines tools important is not that they are used by many industries whose product is, in turn, used by many more industries. What makes them important before the First World War was that this network provided an amplifying system, not just for expansion of demand and falling costs with economies of scale, but for the learning occurring at both ends. (444)

2. See the studies presented in Rosenberg (1976, 1982) and the contributions of Abernathy and Utterback (1975, 1978), Clark (1985) and von Hippel (1988).
3. Adner and Levinthal (2002, 54) cited the case of the disk drive industry, in which the attributes of size, weight and power requirement become relevant to the niche of portable computers.
4. See, for example, Abernathy and Utterback (1975, 1978), Clark (1985) and von Hippel (1988).
5. On the framework structure–process–function in organization thinking, see Lane et al. (2009).
6. On the key role of complementarities in innovation processes, see Rosenberg (1976). Teece (1986) focused on the role of complementary assets. Russo (2000) explored the links between innovation, complementary activities and industrial dynamics.
7. For a review of some classical cases of exaptation, see Dew, Sarasvathy, and Venkataraman (2004) and Bonifati and Villani (forthcoming). According to Mokyr (2000, 57–8), exaptation phenomena are a ubiquitous characteristic in the history of technology.
8. I refer to Antonelli (2009) for an analysis of the economics of innovation from its classical legacies to the economics of complexity.
9. For a historical survey of the meaning of the term degeneracy, see Mason (2010).
10. On the idea that in social and cultural systems linkages emerge from interacting processes, see Wolf (1982). For an application of that idea in the context of 'On the Development Systems Theory', see Oyama et al. (2001).
11. See Dopfer, Foster, and Potts (2004) for a discussion of this methodological framework.
12. Sources of case studies reported below can be found in a broad and detailed study in Bonifati (2008), in particular, in chaps. 4, 8 and 10, pages 81–94, 139–57 and 181–212, respectively.
13. Bonifati (2010) argued that 'this example reveals that "more is different": quantitative changes in scale of the potential production produce qualitative changes in the relation between production, technology and consumption' (751).
14. See Cipolla (1969, chap. 2).
15. See Novati (1907, 89–117), Bonifati (2008, 143–5, 186) and references herein.
16. In the ancient meaning, 'ciurmatore' is every seller that sells cheap goods.
17. See Conway (1999, 131, 195, 225) and Bonifati (2008, 186).
18. Lane and Maxfield (1997, 194–5) defined these interactions as 'generative relationships' and characterized them by the following five properties: (a) *heterogeneity*, (b) *aligned directedness*, (c) *mutual directedness*, (d) *permissions* and (e) *opportunities of action*.
19. For more details, see Bonifati and Villani (forthcoming) in which the paradigm of 'adaptation through selection' was examined with reference to Nelson and Winter's (1982) theory of economic change. On the non-derivability of the historical origin from the current functionality in biological systems and in human institutions, see Gould (2002, 1215–18) and Nietzsche (1887) quoted by Gould (2002).
20. From this point of view, the concept of degeneracy, related to economic and social processes, has similarities with concepts such as that of equifinality – used in organizational analysis to acknowledge that there is more than one way to succeed in each type of setting (Meyer, Tsui, and Hinings 1993) – and modularity, used both in the analysis of complementarities in modern manufacturing (Milgrom and Roberts 1990, 1995) and in the analysis of organizational systems built by firms to increase flexibility (Schilling 2000; Schilling and Steensma 2001).

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